THE LATITUDINAL DISTRIBUTION OF SUNSPOT AREA AND VARIATIONS OF THE DIFFERENTIAL ROTATION OF THE SUN DURING THE PERIOD 1921-1971

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ABSTRACT. The distribution of the sunspot area is compared with the distribution of variations of the differential rotation in solar activity cycles nos 16 - 20 using butterfly diagrams. The variations of the differential angular rotation of the Sun for a particular year and latitude zone are defined as the difference between the average annual value of the daily sidereal angular rotation of sunspots and the average long-term (1921-1982) value of the same quantity. Gilman et al. (1984) published the basic observation material related to the differential rotation. The analysis indicates that the zones on the Sun in which there is a large accumulation of sunspot areas display a smaller velocity than the long-term average zonal velocity (Tab. 3). The cases with faster rotation have an average annual value of the zonal sunspot area equal to 32000 millionths of the Sun's visible hemisphere (areal unit). The cases with slow rotation have an average annual value of the zonal area equal to 55000 units.

ШИРОТНОЕ РАСПРЕДЕЛЕНИЕ ПЛОЩАДИ СОЛНЕЧНЫХ ПЯТЕН И ВАРИАЦИИ ДИФФЕРЕНЦИАЛЬНОГО ВРАЩЕНИЯ СОЛНЦА В ТЕЧЕНИИ ПЕРИОДА 1921-1971. В мотыльковых диаграммах с 16 по 20 - й цикл солнечной активности были между собой сравнены распределения наличия площадей пятен и вариации дифференциального вращения Солнца. Вариации дифференциальной угловой скорости вращения Солнца для каждого года в данной широтной зоне были определены как разница годичного и многолетнего (1921-1982)

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значения средней дневной сидерической скорости. Гилман и др. (1984) опубликовали основные наблюдения дифференциального вращения пятен. Результаты работы показывают, что для тех широтных зон, в которых в определенном году наблюдается большое накопление площадей пятен, получается значение зональной скорости меньше многолетнего (Таб. 3). Для тех зон, в которых наблюдается повышенная вращательная скорость пятен, имеет средняя зональная годичная сумма площадей пятен значение 32000 миллионной доли площади видимой полусферы Солнца (единица площади). Для тех зон, в которых наблюдается пониженная вращательная скорость пятен, имеет средняя зональная годичная сумма плпщадей пятен значение 55000 единиц.

ŠÍRKOVÉ ROZDELENIE PLÔCH SLNEČNÝCH ŠKVŔN A VARIÁCIÍ DIFERENCIÁLNEJ RÝCHLOSTI SLNKA POČAS OBDOBIA 1921-1971. V motýľovitých diagramoch cyklov č. 16 - 20 aktivity Slnka sú porovnané rozdelenie výskytu plôch škvŕn s rozdelením variácií diferenciálnej rotácie. Variácie diferenciálnej uhlovej rýchlosti Slnka pre určitý rok a šírkovú zónu sú definované ako rozdiel priemernej ročnej hodnoty dennej siderickej uhlovej rýchlosti škvŕn a priemernej dlhodobej (1921-1982) hodnoty tej istej veličiny. Základný pozorovací materiál o diferenciálnej rotácii publikovali Gilman et al. (1984). Z práce plynie, že tie zóny na Slnku, v ktorých je veľká kumulácia plôch škvŕn sa vyznačujú menšou rýchlosťou ako je dlhodobý priemer (Tab. 3). Prípady s rýchlejšou rotáciou majú priemernú ročnú hodnotu zonálnej plochy škvŕn 32000 miliontín viditeľnej hemisféry Slnka. Prípady s pomalšou rotáciou majú priemernú ročnú hodnotu zonálnej plochy škvŕn 55000 miliontín viditeľnej hemisféry Slnka.

1. INTRODUCTION

The variations of solar differential rotation with time, zone and height belong to problems in which a large number of issues still require clarification. The rotation of the solar surface varies with heliographic latitude B as $V(B) = a + b \sin^2 B + c \sin^4 B$. The coefficient a determines the equatorial rotation velocity of the Sun. Spectroscopic methods set the sidereal values of coefficient a at values of 1960 to 2020 ms^{-1} (Küveler et al., 1983; Pierce et al., 1984; Snodgrass, 1985). From the motion of sunspots, Newton et al. (1951) determined coefficient a to be 2020 ms^{-1}, which is good agreement with the spectroscopic method. Coefficient b represents the differential rotation.

Apart from variations of the differential rotation with time and latitude, also variations related to solar activity have been observed (Solonsky, 1972; Deubner and Vazquez, 1975; Godoli and Mazzucconi, 1983). Outside the activity zone, i.e. for regions with heliographic latitude B larger than $\pm 30^{\circ}$, the rotation velocity of the Sun is probably stable in time. Cram et al. (1983) studied the velocity fields in the neighbourhood of the solar poles.

The variations of the differential rotation in the zone where sunspots are generated have been observed to display amplitudes of 100 ms^{-1}. With a view

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to the amplitude of the velocity variations in the activity zone ($\pm$ 30^{o}) one must distinguish between localities which are temporarily quiet and without active regions, and localities which are active. Measurements of the equatorial velocity using spectroscopic methods in the quiet regions were made at the Göttingen Observatory, near Locarno (Pérez-Garde et al., 1981; Küveler et al. 1983), at Kitt Peak Observatory (Duvall, 1982; Balthasar, 1983, 1984), at Stanford Solar Observatory (Scherer et al., 1980) and Mt. Wilson Observatory (Howard et al., 1970).

The relative velocity of sunspot umbras with respect to the quiet photosphere has not been determined definitely yet. There are authors (Foukal, 1972, 1976, 1979; Howard et al., 1970; Koch, 1984; Schröter et al., 1976; Snodgrass, 1983) who claim that the rotation velocity of sunspots is 2 - 10 % hogher than that of the ambient photospheric plasma. This interesting result cannot be generalized yet, because other authors (Beckers, 1977; Adam, 1979; Scherrer et al., 1980) reported no difference between the sunspot velocity relative to the ambient medium.

Most papers on the time variations of coefficients a and b in the course of several activity cycles take sunspot observations as the basis (Arevalo et al., 1982; Balthasar et al., 1980). Differences in the velocities of sunspots were found with regard to their area and magnetic type (Lustig et al., 1984; Gilman et al., 1985).

Some authors studied the dependence of differential rotation on the phase of the 11-year cycle (Antonucci and Dodero, 1977; Letfus and Sýkora, 1982). Some studies indicate that the sunspots rotate faster during the solar activity minimum period than during the maximum period (Balthasar, 1979; Balthasar et al., 1980; Becker, 1954; Chistyakov, 1976; Coffey et al., 1969; Comper et al., 1957; Lustig, 1983; Miller, 1960; Shodo, 1950).

The purpose of this paper is to contribute to the clarification of the occurrence of variations of the differential velocity of sunspots in dependence on the phase of the solar cycle. It is compared the fine structure of the equal sunspot areas determined from butterfly diagrams for cycles nos 16 - 20 with the latitudinal distribution of the variations of rotation velocity. The detailed comparison of the two quantities in the butterfly diagrams will enable us to analyse in greater detail the simultaneous occurrence of increased sunspot areas and the deceleration of the sunspots motion.

2. OBSERVATION MATERIAL

The basic observation material for the years 1921-1971 is given in Tab.1. The variations of the rotation velocity of sunspots and the annual values of sunspot areas are given separately for 14 latitude zones on the Sun. Each zone is 5^{o}wide and they run parallel to the solar equator. The north and south hemisphere are divided into 6 latitude zones, from 0^{o} to 30^{o}, and the 7th zone covers the sunspots whose heliographic latitude is over 30^{o}.

Table 1 is arranged as follows:

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Table 1

The sunspot area and variations of the differential rotation
The southern hemisphere

Year		-30°	-30°-25°	-25°-20°	-20°-15°	-15°-10°	-10°-05°	-05°-00°
1921	Var	...	...	...	+0.06	+0.30	+0.30	+0.04
	SD	...	...	...	0.18	0.16	0.08	0.20
	Area	0	0	0	12	10	40	6
1922	Var	...	...	...	...	-0.82	+0.19	+0.14
	SD	...	...	...	...	0.09	0.24	0.18
	Area	0	0	0	0	4	22	7
1923	Var	...	...	...	...	...	-0.40	...
	SD	...	...	...	...	...	0.71	...
	Area	0	3	0	3	0	2	0
1924	Var	...	+0.21	+0.21	-0.36	...	...	...
	SD	...	0.18	0.23	0.24	...	...	...
	Area	0	9	7	0	0	0	0
1925	Var	-0.41	-0.37	+0.06	+0.14	-0.39	...	...
	SD	0.45	0.14	0.15	0.10	0.08	...	...
	Area	4	7	40	36	27	0	0
1926	Var	...	+0.50	+0.39	+0.03	+0.28	-0.16	...
	SD	...	0.18	0.12	0.06	0.08	0.08	...
	Area	1	30	32	89	54	13	0
1927	Var	...	+0.05	+0.19	+0.24	+0.21	+0.08	-0.63
	SD	...	0.16	0.12	0.05	0.05	0.05	0.16
	Area	0	6	6	80	83	70	1
1928	Var	...	-0.96	-0.13	-0.03	-0.01	+0.15	+0.98
	SD	...	0.18	0.11	0.07	0.07	0.10	0.22
	Area	0	8	26	97	80	27	3
1929	Var	...	...	-0.32	-0.12	-0.06	-0.20	-0.16
	SD	...	...	0.14	0.08	0.08	0.05	0.07
	Area	0	0	14	25	62	88	26
1930	Var	...	...	...	+1.16	-0.03	-0.23	-0.18
	SD	...	...	...	0.12	0.13	0.08	0.18
	Area	0	0	0	17	8	43	14
1931	Var	...	...	...	-0.35	-0.75	-0.32	-0.40
	SD	...	...	...	0.43	0.17	0.10	0.18
	Area	0	0	0	6	5	9	7
1932	Var	...	...	...	...	...	-0.02	-0.52
	SD	...	...	...	...	...	0.12	0.17
	Area	0	0	0	0	2	12	1

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Table 1 continued

1933	Var	...	...	...	...	...	+0.97	...
	SD	...	...	...	...	...	0.13	...
	Area	0	0	0	0	0	1	0
1934	Var	-0.21	-0.28	...	+0.78	...	...	...
	SD	0.28	0.13	...	0.35	...	...	...
	Area	6	17	3	1	0	0	0
1935	Var	-0.11	+0.08	-0.19	0.00	+0.25	+0.55	...
	SD	0.11	0.08	0.07	0.09	0.24	0.13	...
	Area	16	50	45	30	10	1	0
1936	Var	-0.03	-0.14	-0.14	+0.06	-0.10	+0.15	...
	SD	0.15	0.11	0.08	0.07	0.09	0.12	...
	Area	36	42	53	55	50	11	0
1937	Var	-0.34	+0.43	-0.03	-0.23	-0.09	+0.02	...
	SD	0.22	0.16	0.14	0.20	0.05	0.07	...
	Area	2	12	47	76	95	40	0
1938	Var	+0.08	-0.39	-0.08	+0.13	-0.17	+0.08	-0.18
	SD	0.27	0.20	0.08	0.06	0.05	0.06	0.09
	Area	1	24	56	59	150	111	9
1939	Var	...	-0.23	+0.16	+0.05	-0.14	-0.03	-0.19
	SD	...	0.18	0.11	0.06	0.05	0.06	0.09
	Area	0	2	18	89	124	83	24
1940	Var	...	...	-0.24	-0.20	-0.03	-0.05	-0.06
	SD	...	...	0.18	0.06	0.05	0.04	0.06
	Area	0	0	3	29	74	72	18
1941	Var	...	...	...	+0.34	-0.01	+0.09	+0.13
	SD	...	...	...	0.15	0.08	0.08	0.09
	Area	0	0	0	11	17	32	24
1942	Var	...	...	...	-0.18	-0.09	+0.24	-0.28
	SD	...	...	...	0.18	0.09	0.08	0.10
	Area	0	0	0	1	23	30	9
1943	Var	...	...	-0.81	...	+0.21	+0.40	+0.57
	SD	...	...	0.11	...	0.11	0.11	0.13
	Area	0	0	6	0	0	6	3
1944	Var	...	+0.15	+0.15	-0.06	...	-0.16	+0.99
	SD	...	0.18	0.11	0.82	...	0.41	0.14
	Area	1	3	20	4	0	2	1
1945	Var	-0.31	+0.15	+0.04	-0.18	-0.05	-0.10	...
	SD	0.27	0.16	0.10	0.08	0.09	0.12	...
	Area	16	10	36	40	9	2	0

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Table 1 continued

1946	Var	-0.07	+0.25	+0.11	-0.06	-0.05	+0.31	+0.50
	SD	0.14	0.12	0.07	0.05	0.06	0.09	0.14
	Area	20	34	48	75	45	36	0
1947	Var	-0.23	-0.41	+0.01	-0.04	+0.04	-0.04	+0.31
	SD	0.26	0.08	0.06	0.04	0.05	0.06	0.21
	Area	15	25	206	150	124	59	+7
1948	Var	+0.06	+0.26	-0.14	+0.15	+0.05	-0.11	+0.15
	SD	0.47	0.21	0.07	0.07	0.05	0.06	0.07
	Area	2	12	37	74	130	108	19
1949	Var	...	+0.03	-0.09	-0.06	-0.16	+0.09	-0.16
	SD	...	0.29	0.10	0.06	0.05	0.05	0.06
	Area	1	3	19	66	117	90	51
1950	Var	...	-0.76	-0.15	-0.16	-0.20	+0.03	+0.25
	SD	...	0.18	0.12	0.07	0.05	0.06	0.09
	Area	0	1	9	62	50	28	15
1951	Var	...	...	-0.41	-0.07	-0.02	-0.05	-0.08
	SD	...	...	0.24	0.14	0.06	0.05	0.09
	Area	0	0	9	12	54	55	15
1952	Var	...	...	-0.19	-0.18	-0.13	+0.09	-0.22
	SD	...	...	0.21	0.19	0.14	0.06	0.08
	Area	0	0	2	2	23	25	24
1953	Var	...	...	...	...	-0.57	-0.57	+0.86
	SD	...	...	...	...	0.18	0.15	0.40
	Area	0	0	0	0	5	8	1
1954	Var	...	...	+0.09	...	...	...	...
	SD	...	...	0.09	...	...	...	...
	Area	2	0	2	0	0	4	0
1955	Var	+0.47	+0.40	+0.15	-0.70	...	...	...
	SD	0.17	0.19	0.08	0.10	...	...	...
	Area	8	13	52	9	0	0	0
1956	Var	+0.05	-0.09	-0.14	-0.21	-0.13	+0.30	...
	SD	0.31	0.09	0.05	0.04	0.06	0.19	...
	Area	11	54	191	118	44	1	0
1957	Var	-0.54	+0.04	+0.10	+0.08	+0.05	+0.24	+0.46
	SD	0.14	0.10	0.07	0.05	0.06	0.11	0.22
	Area	42	97	170	152	98	19	4
1958	Var	-0.51	+0.24	+0.09	-0.01	+0.03	+0.02	+0.07
	SD	0.16	0.12	0.07	0.05	0.04	0.06	0.08
	Area	5	22	94	184	161	81	35

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Table 1 continued

1959	Var	-0.15	...	-0.45	-0.21	-0.22	-0.21	+0.01
	SD	0.24	...	0.11	0.07	0.07	0.06	0.10
	Area	5	1	17	83	76	45	18
1960	Var	...	...	-0.10	-0.09	-0.10	-0.04	+0.09
	SD	...	...	0.19	0.07	0.05	0.05	0.10
	Area	0	0	11	49	84	61	12
1961	Var	...	...	...	+0.16	+0.07	-0.06	-0.23
	SD	...	...	...	0.14	0.10	0.06	0.10
	Area	0	0	0	5	9	38	9
1962	Var	...	...	-0.01	-0.41	-0.09	+0.17	+0.32
	SD	...	...	0.22	0.16	0.11	0.16	0.24
	Area	0	0	1	3	28	15	6
1963	Var	...	...	...	+0.02	+0.03	+0.07	+1.93
	SD	...	...	...	0.09	0.08	0.21	0.21
	Area	0	0	0	3	10	8	1
1964	Var	...	...	...	...	...	+1.09	...
	SD	...	...	...	...	...	0.47	...
	Area	0	0	0	0	0	1	2
1965	Var	...	+0.14	...	...	...	...	...
	SD	...	0.96	...	...	...	...	...
	Area	0	1	0	2	2	0	0
1966	Var	+0.73	+0.10	-0.08	+0.36	...	...	...
	SD	0.38	0.30	0.09	0.41	...	...	...
	Area	0	1	18	2	0	0	0
1967	Var	+0.57	-0.03	+0.11	-0.09	+0.13	...	...
	SD	0.69	0.14	0.06	0.06	0.16	...	...
	Area	2	26	97	90	14	4	0
1968	Var	+0.33	+0.44	+0.08	+0.14	-0.04	+0.33	+0.47
	SD	0.17	0.15	0.09	0.07	0.06	0.12	0.22
	Area	21	25	29	62	79	8	5
1969	Var	+0.23	+0.02	+0.26	+0.06	-0.07	-0.01	+0.64
	SD	0.18	0.11	0.15	0.06	0.05	0.07	0.13
	Area	9	3	11	48	86	23	4
1970	Var	...	...	+0.47	+0.26	+0.31	-0.12	+0.04
	SD	...	...	0.14	0.08	0.05	0.04	0.09
	Area	2	2	16	39	100	78	20
1971	Var	...	+0.26	+0.09	+0.24	+0.11	+0.29	+0.05
	SD	...	0.18	0.12	0.06	0.05	0.08	0.09
	Area	0	0	1	26	81	68	19

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Table 1 continued
The northern hemisphere

Year		00°+05°	+05°+10°	+10°+15°	+15°+20°	+20°+25°	+25°+30°	+30°
1921	Var	-0.35	+0.26	-0.09	+0.59	...	...	...
	SD	0.09	0.09	0.07	0.31	...	...	...
	Area	27	41	20	2	0	0	0
1922	Var	...	+0.31	+0.21	...	...	...	...
	SD	...	0.11	0.15	...	...	...	...
	Area	1	42	16	0	0	0	0
1923	Var	...	-0.34	-0.54	...	...	...	...
	SD	...	0.15	0.27	...	...	...	...
	Area	2	6	0	0	1	3	0
1924	Var	...	+0.25	...	-0.02	+0.17	-0.08	+0.03
	SD	...	0.16	...	0.12	0.10	0.20	0.11
	Area	2	7	1	13	38	5	18
1925	Var	...	...	+0.42	+0.11	0.00	+0.08	+0.09
	SD	...	...	0.15	0.10	0.08	0.19	0.34
	Area	0	1	11	59	96	18	3
1926	Var	...	-0.01	+0.10	+0.23	-0.12	+0.22	...
	SD	...	0.06	0.10	0.08	0.06	0.10	...
	Area	0	28	17	59	123	10	1
1927	Var	-0.37	+0.05	0.00	-0.02	-0.04	-0.30	-0.33
	SD	0.17	0.10	0.06	0.06	0.10	0.16	0.22
	Area	3	13	36	44	22	3	17
1928	Var	-0.11	-0.15	-0.09	+0.15	+0.06	-0.11	...
	SD	0.16	0.07	0.07	0.08	0.09	0.12	...
	Area	6	110	70	71	6	1	0
1929	Var	+0.23	-0.01	+0.04	-0.16	+0.25	...	...
	SD	0.14	0.05	0.04	0.08	0.11	...	...
	Area	24	85	81	42	5	0	0
1930	Var	+0.17	-0.14	-0.02	-0.14	+0.72	+0.27	...
	SD	0.20	0.06	0.09	0.09	0.34	0.62	...
	Area	10	37	36	20	1	1	0
1931	Var	+0.09	+0.02	-0.11	...	...	...	...
	SD	0.18	0.09	0.12	...	...	...	...
	Area	12	44	15	2	1	0	0
1932	Var	-0.05	-0.06	-0.02	...	...	...	...
	SD	0.09	0.13	0.11	...	...	...	...
	Area	13	13	24	1	0	0	0

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Table 1 continued

1933	Var	+0.13	+0.16	+0.20	+0.41	...	...	...
	SD	0.15	0.16	0.07	0.12	...	...	...
	Area	4	8	19	1	0	0	0
1934	Var	-0.81	+0.16	...	...	...	-0.12	...
	SD	0.18	0.22	...	...	...	0.11	...
	Area	5	2	0	0	4	5	0
1935	Var	...	...	+0.11	+0.37	+0.14	-0.27	-0.43
	SD	...	...	0.08	0.09	0.07	0.08	0.19
	Area	1	0	4	11	34	18	5
1936	Var	...	...	+0.45	+0.22	+0.01	+0.28	+0.23
	SD	...	...	0.11	0.06	0.07	0.13	0.17
	Area	0	5	29	70	37	15	12
1937	Var	...	+0.05	+0.11	-0.09	-0.16	-0.04	-0.42
	SD	...	0.08	0.04	0.06	0.26	0.12	0.11
	Area	1	113	125	91	59	31	60
1938	Var	-0.11	-0.12	+0.05	+0.01	-0.11	+0.31	+0.06
	SD	0.23	0.09	0.06	0.08	0.98	0.13	0.32
	Area	10	47	101	100	37	29	1
1939	Var	+0.03	+0.07	-0.26	-0.11	-0.11	-0.15	+0.69
	SD	0.14	0.07	0.05	0.06	0.08	0.13	0.33
	Area	14	46	88	40	30	18	1
1940	Var	+0.06	-0.07	-0.12	+0.02	+0.64	+0.95	...
	SD	0.14	0.04	0.06	0.10	0.15	0.54	...
	Area	5	53	85	36	4	1	0
1941	Var	+0.13	+0.08	+0.11	-0.08	+0.31	-0.14	...
	SD	0.16	0.08	0.06	0.07	0.26	0.28	...
	Area	18	21	105	13	1	1	0
1942	Var	-0.01	+0.06	+0.14	-0.30	+0.57	...	...
	SD	0.16	0.07	0.09	0.12	0.31	...	...
	Area	3	60	21	8	1	0	0
1943	Var	+0.11	-0.07	-0.19	+0.12	...	...	...
	SD	0.13	0.06	0.05	0.13	...	...	...
	Area	23	41	20	7	0	0	0
1944	Var	...	...	...	-0.19	-0.12	...	...
	SD	...	...	...	0.27	0.30	...	...
	Area	2	1	0	6	6	1	0
1945	Var	...	+0.86	+1.23	-0.27	+0.34	+0.29	+0.84
	SD	...	0.24	0.07	0.22	0.14	0.12	0.52
	Area	0	1	1	5	22	15	1

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Table 1 continued

1946	Var	...	-0.43	-0.09	-0.09	-0.12	0.00	+0.02
	SD	...	0.14	0.05	0.05	0.05	0.07	0.10
	Area	0	18	68	65	136	102	15
1947	Var	+0.26	+0.21	-0.07	+0.15	+0.09	-0.05	+0.41
	SD	0.21	0.09	0.05	0.05	0.04	0.08	0.16
	Area	1	25	126	116	79	13	3
1948	Var	-0.02	+0.19	-0.12	-0.17	-0.15	+0.04	...
	SD	0.20	0.06	0.05	0.07	0.07	0.18	...
	Area	6	59	129	69	70	8	1
1949	Var	-0.29	-0.16	-0.03	+0.02	-0.05	0.00	...
	SD	0.14	0.06	0.04	0.05	0.05	0.16	...
	Area	49	103	112	60	28	8	1
1950	Var	+0.05	-0.14	-0.07	+0.07	+0.35	-0.06	+0.24
	SD	0.09	0.05	0.04	0.06	0.12	0.19	0.60
	Area	10	77	114	37	27	14	2
1951	Var	-0.08	+0.07	-0.12	-0 .20	+0.11	...	...
	SD	0.12	0.05	0.05	0.06	0.15	...	...
	Area	8	81	140	22	13	0	0
1952	Var	+0.17	+0.04	-0.11	+0.09	...	...	...
	SD	0.08	0.07	0.07	0.22	...	...	...
	Area	20	29	20	3	0	0	0
1953	Var	+0.31	+0.31	+0.16	-0.39	-0.18	...	...
	SD	0.24	0.45	0.13	0.22	0.31	...	...
	Area	8	4	23	1	1	0	0
1954	Var	...	...	...	...	...	+1.16	...
	SD	...	...	...	...	...	0.27	...
	Area	0	0	0	0	1	1	3
1955	Var	...	...	...	-0.43	-0.18	-0.16	+0.16
	SD	...	...	...	0.15	0.08	0.10	0.11
	Area	0	0	0	16	58	30	20
1956	Var	...	...	+0.14	+0.06	+0.05	0.00	-0.05
	SD	...	...	0.07	0.06	0.04	0.06	0.09
	Area	0	0	41	105	197	61	48
1957	Var	-0.15	+0.05	-0.02	-0.15	+0.01	+0.09	+0.14
	SD	0.33	0.09	0.05	0.05	0.07	0.09	0.13
	Area	0	50	135	117	120	63	41
1958	Var	-0.06	+0.01	+0.07	+0.12	+0.17	-0.14	-0.18
	SD	0.16	0.06	0.06	0.06	0.06	0 07	0.12
	Area	7	61	114	108	103	78	50
1959	Var	-0.01	-0.13	+0.11	-0.17	-0.03	0.00	+0.21
	SD	0.10	0.04	0.04	0.05	0.06	0.08	0.18
	Area	30	192	249	220	89	64	13

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Table 1 continued

1960	Var	-0.13	+0.09	+0.02	-0.07	-0.10	+0.06	-0.01
	SD	0.15	0.06	0.05	0.05	0.05	0.09	0.16
	Area	4	92	83	79	105	57	3
1961	Var	-0.07	-0.15	+0.20	+0.10	-0.05	...	...
	SD	0.08	0.07	0.07	0.08	0.08	...	...
	Area	31	46	48	28	10	0	0
1962	Var	-0.37	-0.18	-0.09	-0.13	-0.01	...	...
	SD	0.13	0.06	0.06	0.08	0.08	...	...
	Area	10	68	26	7	5	0	0
1963	Var	-0.10	+0.39	+0.29	-0.09	...	...	...
	SD	0.33	0.12	0.11	0.10	...	...	...
	Area	7	25	47	4	0	0	1
1964	Var	...	+0.09	-0.34	...	...	...	...
	SD	...	0.21	0.37	...	...	...	...
	Area	1	7	1	1	2	1	2
1965	Var	...	+0.53	+1.16	+0.05	-0.01	-0.01	...
	SD	...	0.38	0.44	0.14	0.08	0.15	...
	Area	1	3	2	3	16	7	1
1966	Var	-0.41	-0.35	-0.23	-0.13	+0.02	+0.02	+0.02
	SD	0.37	0.19	0.14	0.09	0.06	0.11	0.13
	Area	1	41	15	42	83	36	18
1967	Var	...	-0.17	-0.01	+0.09	-0.11	-0.43	...
	SD	...	0.09	0.05	0.06	0.07	0.11	...
	Area	0	16	76	94	127	72	10
1968	Var	+0.50	0.00	-0.12	+0.03	0.00	+0.19	-0.17
	SD	0.19	0.07	0.04	0.05	0.09	0.10	0.43
	Area	6	27	166	95	52	11	10
1969	Var	+0.18	+0.01	-0.01	+0.05	-0.06	+0.24	+0.03
	SD	0.18	0.05	0.05	0.08	0.08	0.23	0.97
	Area	13	77	145	48	49	49	6
1970	Var	-0.03	-0.05	+0.06	+0.07	-0.10	-0.11	...
	SD	0.09	0.06	0.05	0.04	0.06	0.12	...
	Area	19	39	74	164	44	2	0
1971	Var	+0.03	+0.16	-0.03	+0.04	+0.04	-0.16	...
	SD	0.10	0.06	0.06	0.08	0.27	0.11	...
	Area	14	60	23	30	4	1	0

Line 1 - Variations of the differential velocity. It is known that the sunspot rotation rates display a large scatter. The average values of the sidereal daily angular velocities of sunspots for the years 1921-1982, as published by Gilman et al. (1984), were taken as the reference system of

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differential velocity. The variation of the differential velocity is defined as the difference between the average annual value of the sidereal daily angular velocity and the long-term average value of the same quantity. The variations have been calculated for all 14 zones. The difference is given in fractions of heliographic degree per day. The + sign indicates faster and the - sign slower rotation than the long-term average.

Line 2 - Standard deviation of the difference between the annual and long-term (1921-1982) values of the sidereal daily angular velocity.

Line 3 - Annual value of areas of whole sunspots (umbra plus penumbra) which occurred in the latitude zone. The annual areas of sunspots were calculated using the method of Antalová and Gnevyshev (1983). The basic daily values of the corrected sunspot areas were published in the Greenwich Observations. The annual values of the sunspot areas were calculated by adding up the areas of all sunspots observed in the particular zone each day. This method of adding the areas not only emphasizes the frequency of sunspot generation, but also their size and lifetime. The annual values of the sunspot areas in the appropriate zone are given in thousandths of the visible hemisphere of the Sun (TSH). For example, the value 4 stands for 4000 millionths of the Sun's visible hemisphere, which is unit used in measuring the sunspot area.

3. METHOD OF TREATMENT

In processing the velocity variations, only those cases were considered for which the value of the variation was sufficiently large with regard to the measurement error. If the difference between the annual and long-term zonal velocities was at least double the standard deviation of the appropriate measurement, the case was considered statistically significant. This method was used to calculate the data for Tab. 2 from those in Tab. 1. Table 2 is arranged as follows:

Column 1 - the current year.

Column 2 - marked 0. It gives the number of zonal cases in the current year in which the difference between the annual and long-term average sunspot velocity was smaller than double the standard deviation (SD).

Column 3 - marked + . This gives the number of zonal cases in the current year in which the difference between the annual and long-term velocities was larger than double the SD. These are the cases of the faster zonal rotation of sunspots.

Column 4 - marked - . This gives the number of zonal cases in the current year for which the velocity variation was smaller than double the SD. These are the cases of slower zonal rotation.

Column 5 - marked S . This gives the sum of all measurements of the variation in the current year (the sum of the figures in Columns 2-4).

Columns 6 and 7 - give the data on the position of the faster zones and simul-

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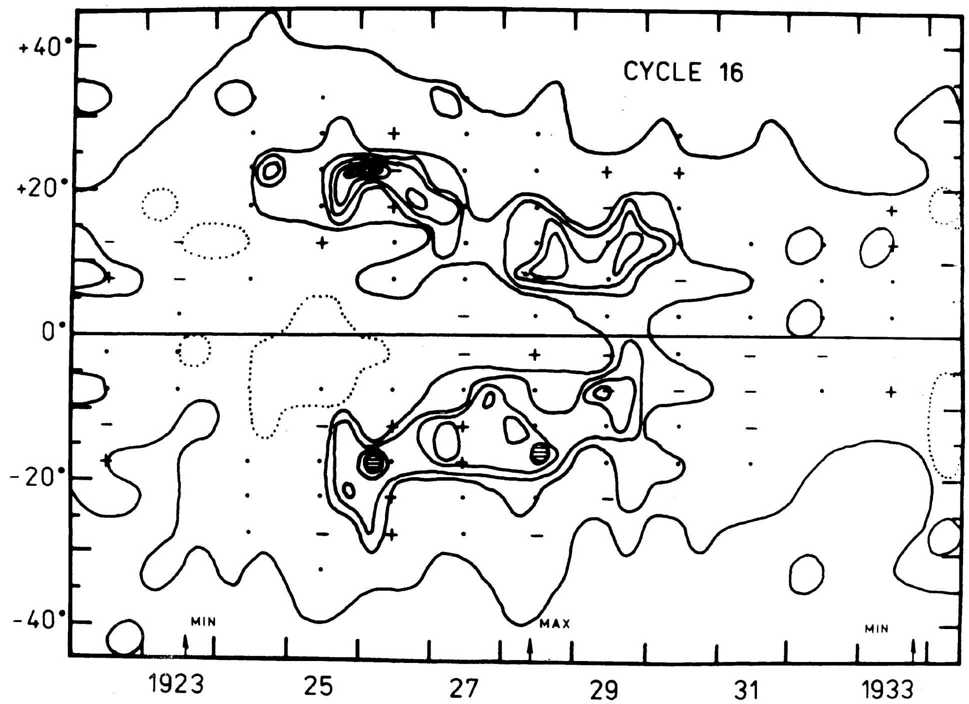

Fig. 1: The distribution of semi-annual sunspot areas as a function of heliographic latitude in the 16th cycle. The lowest contour of the sunspot area is 10000 millionths of the Sun's visible hemisphere (MSH) and the other contours are drawn in steps of 10000 MSH, i.e. 20000, 30000, 40000 MSH. The values of the area from 60000 to 80000 MSH are horizontally hatched and values higher than 80000 MSH are cross-hatched. The annual latitudinal variations of the differential rotation for the 16th cycle are marked with the + or - sign. + indicates cases of faster zonal rotation, - cases with slower zonal rotation, and the dots cases of normal rotation relative to the long-term average (1921 - 1982). The values of the zonal velocities were adopted from the paper by Gilman et al. (1984).

taneously, the annual value of the areas of sunspots in the faster zone. The number of zones is identical with the figure in Column 3.

Columns 8 and 9 - give the data on the position and annual value of the sunspot areas for the slower zones. The number of slower zones must agree with the figure in Column 4.

The analysis of the velocity variations according to the criterion mentioned (the difference must be larger than twice the SD) is illustrated in Figs 1 - 5 for cycles 16 - 20. The sign convection used in Figs 1 - 5 is the same

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Table 2

The statistically significant variations of the differential rotation

Year	0	+	–	S	The faster zones	Area	The slower zones	Area
1921	5	2	1	8	$-05^{o}-10^{o}$	40	$00^{o}+05^{o}$	27
					+05 +10	41		
1922	3	1	1	5	+05 +10	42	-10 -15	4
1923	1	0	2	3			+05 +10	6
							+10 +15	1
1924	8	0	0	8				
1925	7	1	2	10	+10 +15	11	-25 -30	47
							-10 -15	27
1926	4	5	1	10	-25 -30	30	+20 +25	123
					-20 -25	32		
					-10 -15	54		
					+15 +20	59		
					+25 +30	10		
1927	9	2	2	13	-15 -20	80	00 -05	1
					-10 -15	83	00 +05	3
1928	9	1	2	12	00 -05	3	-25 -30	8
							+05 +10	111
1929	5	1	4	10	+20 +25	5	-20 -25	14
							-05 -10	88
							00 -05	26
							+15 +20	42
1930	7	1	2	10	+20 +25	0	-10 -15	8
							+05 +10	37
1931	4	0	3	7			-10 -15	5
							-05 -10	9
							00 -05	7
1932	4	0	1	5			00 -05	1
1933	2	3	0	5	-10 -15	1		
					+10 +15	19		
					+15 +20	1		
1934	3	1	2	6	-15 -20	1	-25 -30	17
							00 +05	5
1935	5	2	4	11	-10 -15	10	-20 -25	45
					+15 +20	11	+20 +25	34
							+25 +30	18

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Table 2 continued

1935							larger +30°	5
1936	8	3	0	11	+10°+15°	29		
					+15 +20	70		
					+25 +30	15		
1937	10	2	0	12	-25 -30	12		
					+10 +15	125		
1938	10	2	2	14	-15 -20	59	-10 -15	150
					+25 +30	29	00 -05	9
1939	9	1	3	13	larger +30	1	-10 -15	124
							00 -05	24
							+10 +15	88
1940	8	1	2	11	+20 +25	4	+10 +15	85
1941	9	1	0	10	-15 -20	11		
1942	5	2	2	9	-05 -10	30	00 -05	9
					+20 +25	1	+15 +20	8
1943	3	3	2	8	-10 -15	1	-20 -25	6
					-05 -10	6	+10 +15	20
					00 -05	3		
1944	6	1	0	7	00 -05	1		
1945	7	4	1	12	+05 +10	1	-15 -20	40
					+10 +15	1		
					+20 +25	22		
					+25 +30	15		
1946	8	3	2	13	-25 -30	34	+05 +10	18
					-05 -10	36	+20 +25	136
					00 -05	1		
1947	9	4	1	14	+05 +10	25	-20 -25	206
					+15 +20	116		
					+20 +25	79		
					larger +30	3		
1948	5	3	5	13	-15 -20	74	-20 -25	37
					00 -05	19	-05 -10	108
					+05 +10	59	+10 +15	129
							+15 +20	69
							+20 +25	70
1949	8	0	4	12			00 -05	51
							00 +05	49
							+05 +10	103
							-10 -15	117

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Table 2 continued

1950	6	2	5	13	00°-05°	15	-25°-30°	1
					+20 +25	27	-15 -20	62
							-10 -15	50
							+05 +10	77
							+10 +15	114
1951	8	0	2	10			+10 +15	140
							+15 +20	22
1952	7	1	1	9	00 +05	20	00 -05	24
1953	5	1	2	8	00 -05	1	-05 -10	8
							-10 -15	5
1954	2	0	0	2				
1955	2	3	3	8	smaller-30	8	-15 -20	9
					-25 -30	13	+15 +20	16
					-20 -25	52	+20 +25	58
1956	7	1	3	11	+10 +15	41	-20 -25	72
							-15 -20	118
							-10 -15	44
1957	10	2	2	14	-05 -10	19	smaller -30	42
					00 -05	4	+15 +20	117
1958	10	2	2	14	+15 +20	108	smaller -30	5
					+20 +25	103	+25 +30	78
1959	6	1	6	13	+10 +15	249	-20 -25	17
							-15 -20	83
							-10 -15	76
							-05 -10	45
							+05 +10	192
							+15 +20	220
1960	10	0	2	12			-10 -15	84
							+20 +25	105
1961	6	1	2	9	+10 +15	48	00 -05	9
							+05 +10	46
1962	7	0	3	10			-15 -20	3
							00 +05	10
							+05 +10	68
1963	4	4	0	8	-05 -10	9		
					00 -05	1		
					+05 +10	25		
					+10 +15	47		
1964	2	1	0	3	-05 -10	1		

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Table 2 continued

1965	5	1	0	6	+10°+15°	2		
1966	11	0	0	11				
1967	8	0	2	10			+20°+25°	127
							+25 +30	72
1968	8	5	1	14	-25 -30	25	+10 +15	166
					-15 -20	62		
					-05 -10	8		
					00 -05	4		
					00 +05	5		
1969	13	1	0	14	00 -05	4		
1970	7	3	1	11	-20 -25	16	-05 -10	78
					-15 -20	39		
					-10 -15	100		
1971	8	4	0	12	-15 -20	26		
					-10 -15	81		
					-05 -10	68		
					+05 +10	60		
Sum	333	83	88	504				
%	66	16	18	100	Mean area	33		55

as that given in detail in Tab. 2, Columns 2 - 4. The contours in Figs 1 - 5 mark the semi-annual values of the zonal areas of whole sunspots (umbra plus penumbra). The marginal contours represent 10000 millionths of the Sun´s visible hemisphere, others 20000, 30000 and 40000 units. The values from 60000 to 80000 units are hatched horizontally and values higher than 80000 units are cross-hatched. The data on the zonal semi-annual values of the sunspot areas were adopted from the paper by Antalová and Gnevyshev (1983).

Table 2 indicates that a total of 504 values of zonal annual velocities measured in the years 1921-1971 were reported in the paper by Gilman et al. (1984). Of these, 333 (66%) were within the 2 SD limit of the long-term average. In 83 cases (16.5%) the difference between the annual and long-term zonal velocities exceeded double the SD, i.e. the zonal sunspot velocity was above the average. 88 values (17.5%) were less than the long-term zonal sunspot rotation velocity.

4. RESULTS AND CONCLUSIONS

1. The analysis can be based on the statistically signicant variations of the differential rotation (Tab. 2, Columns 6 - 9). The average annual value per one faster rotating zone is 33000 millionths of the Sun´s visible hemi-

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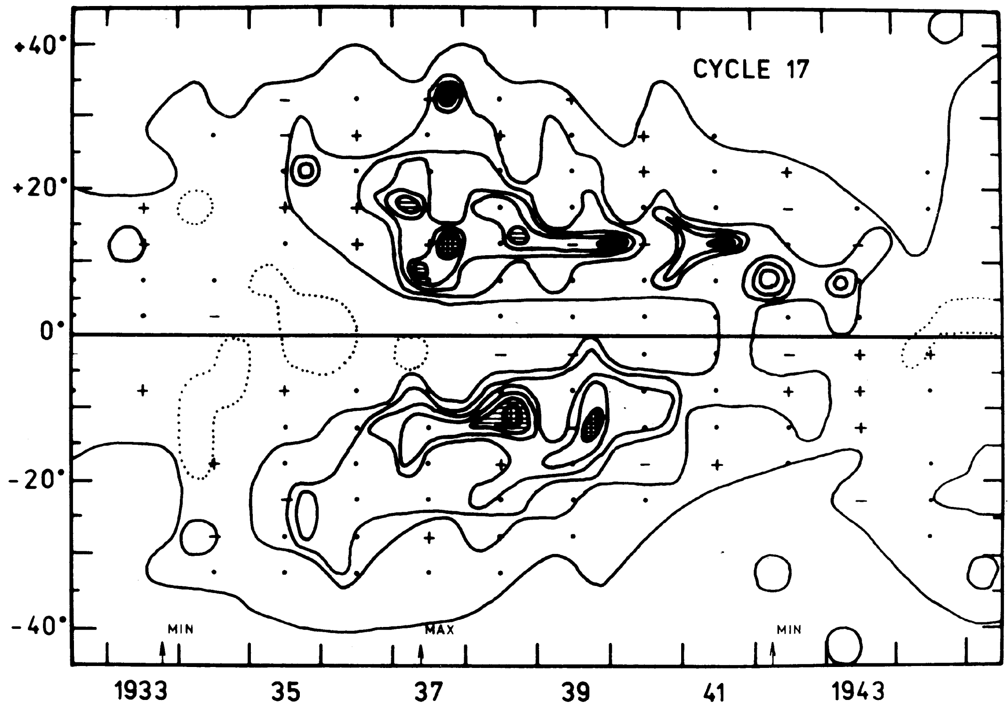

Fig. 2: Latitudinal distribution of sunspot areas and variations of the differential rotation for the 17th cycle of solar activity.

sphere (unit), whereas the average annual value per one slower rotating zone is 55000 units. This shows that the faster zonally rotating sunspots are observed on zones with a lower total average value of all sunspot areas. On the contrary, the more slowly rotating sunspots are located in zones with a larger total sunspot area.

2. The analysis can be based on the annual zonal values of sunspot areas. Let us consider all the cases in which the total annual sunspot area was larger than 100000 units (Tab. 3). Table 3 shows that 47 such instants of sunspot generating activity were observed in 1921-1971. Of these, the zonal rotation was standard in 26 cases. With a view to the long-term distribution, one would expect 66%, i.e. 31 cases. 16.5% should display a faster zonal rotation, i.e. 8 such cases could be expected to occur, but actually only 6 did. 17.5 % should have displayed a slower zonal rotation, i.e. 8 cases, but in fact 15 did.

The distribution of the sunspot area groups by sign does not conform to the expected distribution of velocity variations. The slower rotating sunspots are preferred to the faster rotating sunspots.

3. Besides the preference for the lower velocity in zones with increased occurrence of sunspots, the velocity of sunspot motion also depends on the

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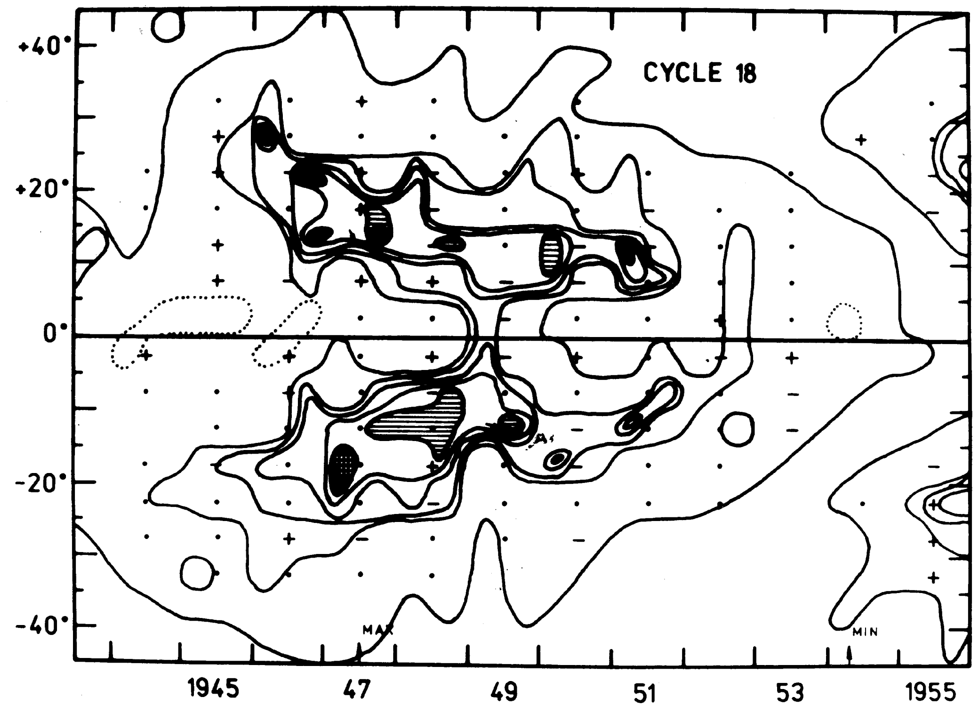

Fig. 3: Latitudinal distribution of sunspot areas and variations of the differential rotation for the 18th cycle of solar activity.

Table 3

The zones with the annual sunspot area larger than 100000 units

No	Year	Zone	Var	SD	Area	Phase	Sign
			Cyclus No. 16				
1	1926	$+20^{\circ}+25^{\circ}$	-0.12	0.06	122813	+3.0 y	-
2	1928	+05 +10	-0.15	0.07	109657	+5.0	-
			Cyclus No. 17				
3	1937	+05 +10	+0.05	0.08	112899	+3.0	0
4	1937	+10 +15	+0.11	0.04	125759	+3.0	+
5	1938	-10 -15	-0.17	0.05	149876	+4.0	-
6	1938	-05 -10	+0.08	0.06	111029	+4.0	0

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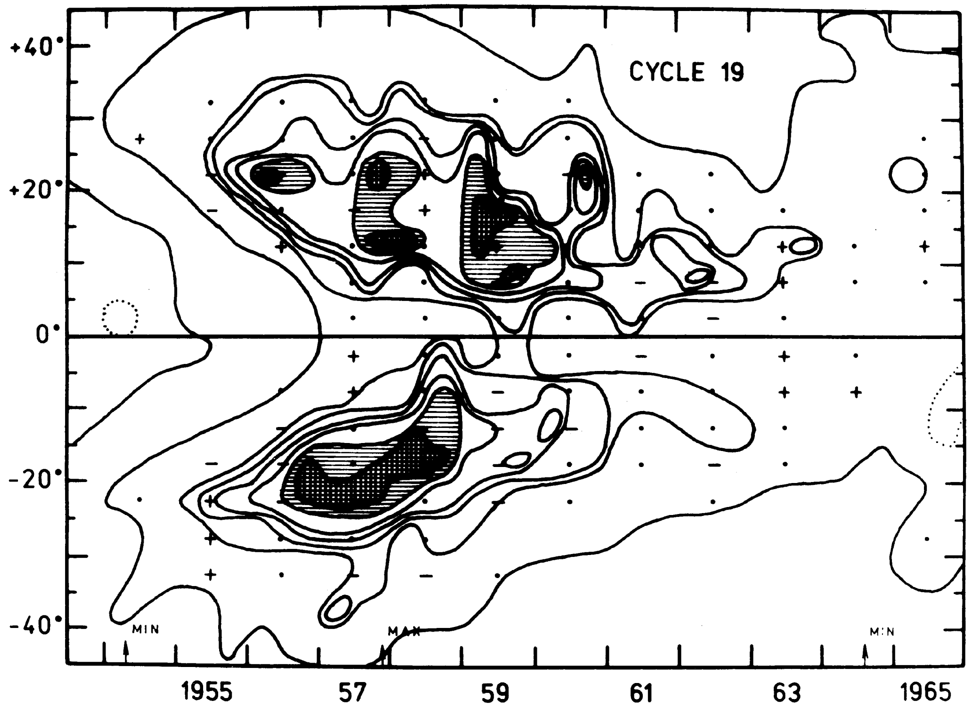

Fig. 4: Latitudinal distribution of sunspot areas and variations of the differential rotation for the 19th cycle of solar activity.

Table 3 continued

7	1938	+10°+15°	+0.05	0.06	100879	+4.0 y	0
8	1938	+15 +20	+0.01	0.08	99901	+4.0	0
9	1939	-10 -15	-0.14	0.05	123254	+5.0	-
10	1941	+10 +15	+0.11	0.06	104997	+7.0	0
			Cyclus No. 18				
11	1946	+20°+25°	-0.12	0.05	136320	+2.0 y	-
12	1946	+25 +30	0.00	0.07	102039	+2.0	0
13	1947	-20 -25	+0.01	0.06	205741	+3.0	0
14	1947	-15 -20	-0.04	0.04	149543	+3.0	0
15	1947	-10 -15	+0.04	0.05	123899	+3.0	0
16	1947	+10 +15	-0.07	0.05	126468	+3.0	0
17	1947	+15 +20	+0.15	0.05	116295	+3.0	+
18	1948	-10 -15	+0.05	0.05	129257	+4.0	0

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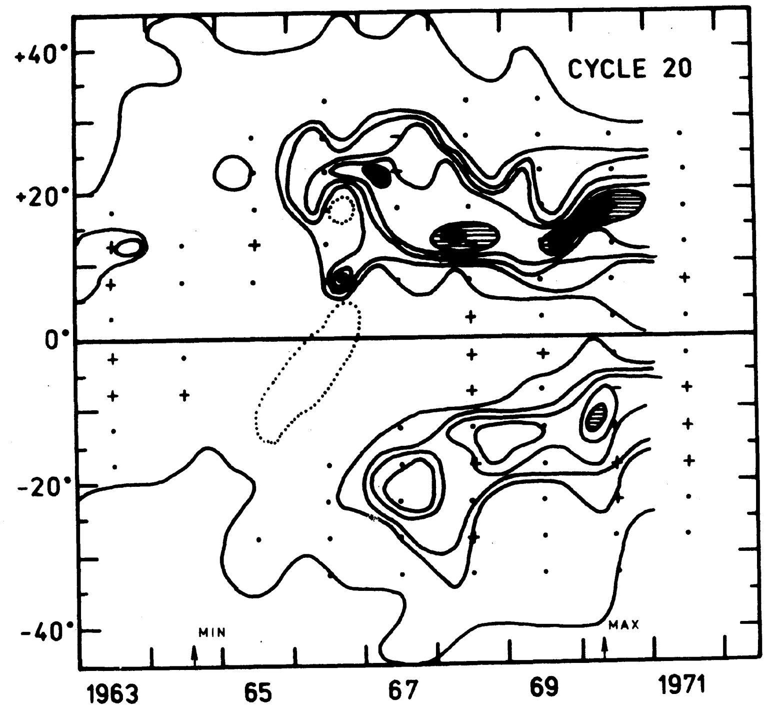

Fig. 5: Latitudinal distribution of sunspot areas and variations of the differential rotation for part of the 20th cycle of solar activity.

Table 3 continued

19	1948	-05°-10°	-0.11	0.06	108136	+4.0 y	0
20	1948	+10 +15	-0.12	0.05	129064	+4.0	-
21	1949	-10 -15	-0.16	0.05	116360	+5.0	-
22	1949	+05 +10	-0.16	0.06	102466	+5.0	-
23	1949	+10 +15	-0.03	0.04	111741	+5.0	0
24	1950	+10 +15	-0.07	0.04	113607	+6.0	0
25	1951	+10 +15	-0.12	0.05	139654	+7.0	-
			Cyclus No. 19				
26	1956	-15°-20°	-0.21	0.04	118101	+2.0 y	-
27	1956	+15 +20	+0.06	0.06	104522	+2.0	0
	1956	-20 -25	-0.14	0.05	191073	+2.0	-
28	1956	+20 +25	+0.05	0.04	197008	+2.0	0
29	1957	-20 -25	+0.10	0.07	169713	+3.0	0

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Table 3 continued

30	1957	$+10^{\circ}+15^{\circ}$	-0.02	0.05	134848	+3.0 y	0
31	1957	+15 +20	-0.15	0.05	116889	+3.0	-
32	1957	+20 +25	+0.01	0.07	120317	+3.0	0
46	1957	-15 -20	+0.08	0.05	151854	+3.0	0
33	1958	-15 -20	-0.01	0.05	183452	+4.0	0
34	1958	-10 -15	+0.03	0.04	161070	+4.0	0
35	1958	+10 +15	+0.07	0.06	114176	+4.0	0
36	1958	+15 +20	+0.12	0.06	107778	+4.0	+
37	1958	+20 +25	+0.17	0.06	103483	+4.0	+
38	1959	+05 +10	-0.13	0.04	191847	+5.0	-
39	1959	+10 +15	+0.11	0.04	248922	+5.0	+
40	1959	+15 +20	-0.17	0.05	219923	+5.0	-
41	1960	+20 +25	-0.10	0.05	105015	+6.0	-
			Cyclus No. 20				
42	1967	$+20^{\circ}+25^{\circ}$	-0.11	0.07	127202	+2.0 y	0
43	1968	+10 +15	-0.12	0.04	165704	+3.0	-
44	1969	+10 +15	-0.01	0.05	145179	+4.0	0
45	1970	-10 -15	+0.31	0.05	99954	+5.0	+
47	1970	+15 +20	+0.07	0.04	163181	+5.0	0

Remark: Phase - phase of cycle of solar activity, expressed in years after the minimum.

phase of the solar cycle. Faster or normal rotation predominates in the first half of the cycle. In the second half of the cycle slower rotation is mostly observed.

It was found that the latitudinal distribution of the annual values of sunspot areas is related to the latitudinal distribution of the velocity variations during cycles nos 16 - 20. Solar zones with a larger cumulation of sunspot areas are characterized by slower zonal rotation relative to the long-term average of the sunspots' rate of motion. The total area of the sunspots in a zone is the function of three parameters: the occurrence frequency of sunspots, the area of the generated sunspots and the lifetime of the sunspots. It is not known which of these three parameters correlates most with the velocity.

The velocity in the photosphere consists of three components: oscillations, convection and rotation. In the above deliberations, we mainly considered the relation between the variation of the differential velocity of sunspots and the distribution of the total sunspot area in the zone. However, it is also possible that the other two components may depend on the distribution of

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the sunspot areas.

To conclude, it should be pointed out that this analysis could be carried out using the semi-annual values of the variations of velocity and area if the authors (Gilman et al., 1984) of the sunspot velocity observations and reductions would provide the data on a finer time scale.

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